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On the evolutionary status of Be stars

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Abstract. We present a study of the incidence of Be stars in open clusters as a function of the cluster age, using whenever possible ages determined through Strömgren $uvby$ photometry. For the first time in studies of this kind we have considered separately classical and Herbig Be stars.

The main results can be summarized as follows:

– Clusters associated to emitting nebulosities and undergoing stellar formation are rich in emission line objects, which most likely are all pre main-sequence stars. No bona fide classical Be star has yet been identified among them.
– Clusters younger than 10 Myr and without associated nebulosity are almost completely lacking Be stars, although they have a complete unevolved B main sequence.
– Classical Be stars appear at an age of 10 Myr, and reach the maximum abundance in the age interval 13-25 Myr.

We interpret our results in the sense that the Be phenomenon is an evolutionary effect which appears in the second half of the main sequence lifetime of a B star. We propose that it can be related to main structural changes happening at this evolutionary phase, which also lead to the recently discovered non-monotonic helium abundance enhancement. The semiconvection or turbulent diffusion responsible of the surface helium enrichment, coupled with the high rotational velocity, can generate magnetic fields via the dynamo effect and thereby originate the Be phenomenon. Observational tests to this hypothesis are proposed.

Key words: stars: emission-line, Be – stars: evolution – Galaxy: open clusters and associations: general

1. Introduction

The evolutionary status of classical Be stars is a frequently raised and yet unsolved question. The main issue is to determine whether the Be phenomenon appears at a given stage in the evolutionary track of every B star, or it originates in the conditions of formation of some stars, which include fast rotation and probably other facts. A fundamental element in this discussion is the study of Be stars in open clusters, in two different ways: i./ the determination of the Be star positions in the cluster photometric diagrams; and, ii./ the study of the abundance of Be stars as a function of the cluster age.

It is well known that Be stars usually occupy anomalous positions in the colour-magnitude diagrams, lying above the main sequence. Early attempts to explain the Be phenomenon suggested that Be stars occur during the core contraction phase following the exhaustion of hydrogen (Schmidt-Kaler 1964). Later, however, it was observed a significant fraction of Be stars close to the ZAMS (Schild & Romanishin 1976), and today it is generally accepted that they occupy the whole main sequence band and different evolutionary states (Mermilliod 1982; Slettebak 1985) and therefore they are not confined to any particular evolutionary phase. It is well established that the anomalous positions in the photometric diagrams can be explained in terms of the contribution of the circumstellar continuum emission to the photometric indices (Fabregat et al. 1996; Fabregat & Torrejón 1998; and references therein).

Extensive studies of the abundances of Be stars in open clusters have been done by Mermilliod (1982) and recently by Grebel (1997). Both authors obtained similar results, finding Be stars in clusters of all ages, with a peak frequency in clusters with turn-off at spectral types B1-B2, and a regular decrease with increasing age afterwards.

Nevertheless, these kind of studies face some difficulties which make their conclusions somewhat uncertain. The purpose of this paper is to critically review the previous work in this field, and to present a new study of the abundance of Be stars in clusters of different ages taking into account new considerations and observational results.

2. Critical review of previous work

In this section we will address the main drawbacks which affect the determination of the Be star abundance as a function of the cluster age. Whenever possible we will propose solutions to these problems.

2.1. The ages of the open clusters

The usual way to determine the age of a star cluster is by means of isochrone fitting. The most extended technique is to transform

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Table 1. Photometric indices commonly used as $T_{\rm eff}$ indicators in the observational HR diagrams.

Index	B range	accuracy	sampling	$E(i)/E(B-V)$
$(B-V)$	0.30	0.010	30	1.0
$(U-B)$	1.00	0.020	50	0.7
$(V-R)$	0.15	0.010	15	0.8
$(V-I)$	0.40	0.010	40	1.6
$(b-y)$	0.10	0.005	20	0.7
c_1	1.10	0.020	55	0.2

the theoretical isochrone from the L - $T_{\rm eff}$ plane to the observational colour-magnitude plane, and then directly compare it with the observational photometric data.

In young open clusters the isochrone fitting is made difficult by two main problems affecting the observational data. The usual presence of differential reddening across the cluster face widens the observed main sequence. For the clusters we are dealing with in this paper, the presence of Be stars which generally occupy anomalous positions in the colour-magnitude diagrams, also contributes to a further main-sequence widening. Hence, the fit of a particular isochrone can be a very uncertain process. For instance, recent age determinations for the cluster with the highest Be star abundance in the Galaxy, NGC 663, are the following: 21 Myr (Leisawitz 1988), 9 Myr (Tapia et al. 1991), 12-15 Myr (Phelps & Janes 1994) and 23 Myr (this work, see below). The difference in the age determinations amounts to a factor of three.

As an attempt to solve this problem, we have investigated the different photometric indices which are commonly used as horizontal axis in the observational HR diagrams, with regard to the B star region of the main sequence. In Table 1 we present for each index its variation along the B star sequence, the photometric accuracy which is usually reached in the photometric data, the sampling of the main sequence – the ratio between the index variation and the accuracy – and how the interstellar reddening affects the index.

In view of this table, the best sampling is obtained with the $(U-B)$ colour in the Johnson system and the c_1 index in the Strömgren system. c_1 has the additional advantage of being much less affected by reddening. Furthermore, the M_V - c_1 diagram allows an efficient segregation of the Be stars from the absorption line B stars (Fabregat et al. 1996). Therefore we propose that the most efficient way to determine reliable ages for very young clusters is the isochrone fitting to the observational M_V - c_1 HR diagram.

In Fig. 1 we present isochrone fitting to the M_V - c_1 photometric diagram for the galactic clusters with the highest Be star abundances. Photometric *uvby* data are from Crawford et al. (1970) and Fabregat et al. (1996) for h and χ Persei (NGC 869 and NGC 884), Tapia et al. (1991) and Fabregat et al. (1996) for NGC 663, and Shobbrook (1985, 1987) for NGC 3766. Only non emission stars have been included in the figure. The assumed reddening and distances to transform the observed V and c_1 into intrinsic M_V and c_0 are $E(b-y)$ = 0.41 (Crawford et al. 1970)

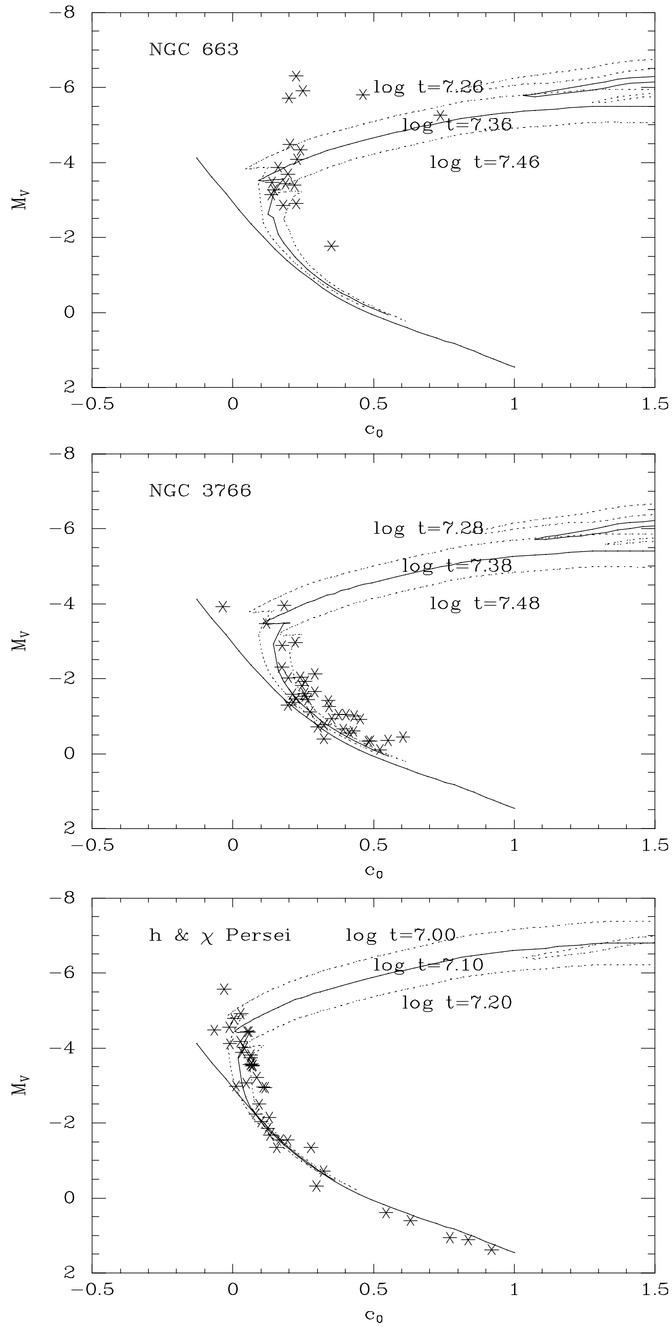

Fig. 1. M_V - c_1 HR diagram for the galactic clusters with the highest Be star abundances.

and DM = 11.16 (Balona & Shobbrook 1984) for h and χ Persei, $E(b-y)$ = 0.59 and DM = 12.25 (Phelps & Janes 1994) for NGC 663 and $E(b-y)$ = 0.15 and DM = 11.43 (Shobbrook 1987) for NGC 3766. Isochrones have been computed with the evolutionary models of Schaller et al. (1992). The best fitting isochrones have been found to correspond to ages of 13 Myr (h and χ Persei), 23 Myr (NGC 663) and 24 Myr (NGC 3766). The uncertainty of the isochrone fitting is well represented by a value of ± 0.1 in $\log t$, which approximately corresponds to an uncertainty of ± 3 Myr at an age of 10 Myr, and to ± 5 Myr at 25 Myr. In Sect. 3 we will base our discussion of the Be star abundances as a function of the cluster age on ages determined in this way.

2.2. Determination of Be star frequencies

Be stars are defined as non-supergiant early-type stars which show or have shown Balmer and other lines in emission. Be stars are found among late O, B and early A-type stars. Through the paper we will use the term “Be star frequency” to denote the fraction of detected Be stars among the total number of main sequence stars earlier than A3 -where the maximum of the Balmer lines tooks place- in a given cluster. We will refer to these stars with the general term “OB stars”. Whenever possible we will use the Be star frequency to measure the abundance of Be stars. However, for many clusters discussed in this paper the number of OB stars is not known. In these cases we will use the total number of detected Be stars as indicator of their Be star abundance.

Spectroscopic surveys devoted to the detection of Be stars in open clusters are scanty in the literature. The only clusters for which the abundance of Be stars have been exhaustively studied are h and χ Persei and NGC 663. The last systematic, although not exhaustive, survey dates from 1976 with the work of Schild & Romanishin (1976).

Most of the known Be stars in open clusters have been identified within the framework of large surveys for emission line stars in the Milky Way, like those conducted at Mount Wilson (Merrill & Burwell 1949), Vatican Observatory (Coyne & MacConnell 1983, and references therein) and Hamburg Observatory (Kohoutek & Wehmeyer 1999), and the searches in the southern hemisphere by Henize (1976), Stephenson & Sanduleak (1977) and MacConnell (1981). All these surveys are magnitude limited, and hence their depth for a given cluster depends upon the cluster distance and reddening. For most clusters only the brightest stars have been searched for line emission. Consequently, the derived Be star abundances are only lower limits, and the completeness of the available data is very difficult to assess.

In the recent years new detection techniques based on CCD imaging photometry are being applied to study the Be star abundances in clusters in the Galaxy (Capilla & Fabregat 2000) and in the Magellanic Clouds (Grebel et al. 1992; Grebel 1997; Keller et al. 1999). However, it has to be kept in mind that photometric surveys never detect the whole content of Be stars by the two following reasons: i./ surveys through photometric filters only detect stars with high level of line emission, loosing the mild emitters which only can be identified by spectroscopic means; ii./ the Be phenomenon is variable, and at a given time only a fraction of Be stars are in a phase of line emission. These studies, however, only provide lower limits of the abundance for no more than 10 clusters. We are still far from having a statistically significant sample of open clusters with well determined Be star frequencies.

2.3. Classical versus Herbig Be stars

In this paper we deal only with the abundances of classical Be stars. There exists other classes of early-type emission line stars. Among them the most conspicuous are the so called Herbig Ae/Be stars. These objects are pre-main sequence stars showing Balmer and other lines in emission. The origin of the line emision is still controversial, but usually interpreted as originating either in a chromospheric stellar or a circumstellar disk wind. For a recent review on Herbig Ae/Be stars, see Waters & Waelkens (1998). The observational characteristics of classical and Herbig Be stars, at least in the optical region, are very similar, making a very difficult task to differenciate between the two types. An efficient segregation can be made in the far-infrared region, where the Herbig Ae/Be stars show an important excess caused by the presence of dust, which is lacking in classical Be stars.

Grebel (1997) includes in her study the clusters NGC 2244, NGC 6611 and IC 2944. All of them are very young open clusters (age $<$ 6 Myr) associated to bright emission nebulosities, and are still undergoing stellar formation (Hillenbrand et al. 1993; Pérez et al. 1987; Reipurth et al. 1997; de Winter et al. 1996). Hillenbrand et al. (1993) found a large number (27) of Hα emission line stars in NGC 6611. They pay special attention to the study of the strong emitters W235 and W503, and show evidence that these stars are Herbig Ae/Be stars instead of classical Be stars. For the rest of the stars the situation is much more uncertain, but they concluded that all emission line stars in NGC 6611 are pre-main sequence objects instead of classical Be stars. De Winter et al. (1996), in a smaller sample in the same cluster, found 11 emission line stars. They classified three of them as Herbig Ae/Be stars, and agreed with Hillenbrand et al. (1993) that most probably the rest of the emission line objects are also pre-main sequence stars.

In the same way, Reipurth et al. (1997) analysed 7 emission line stars in the H II region IC 2944. They classified all of them as young pre-main sequence objects, probably Herbig Ae/Be stars. Van den Anker et al. (1996) found 5 emission line stars in the star-forming cluster NGC 6530. They classified 3 as Herbig Ae/Be, and concluded that the remaining two most probably are of the same type.

We can conclude that, despite the difficulty of differenciating between classical and Herbig Be stars, there are in the literature several positive identifications of Herbig Ae/Be stars in the youngest, star-forming open clusters. Conversely, no bona fide classical Be star has yet been reported among them.

It is interesting to note that in young stellar forming clusters only a fraction of the pre-main sequence stars are actually Herbig Ae/Be stars. This suggests that either this is a transitory phenomenon or that it requires specific conditions to develop, much like the classical Be stars. This may indicate the existence of some connection between these two classes of objects, and indeed very recently the existence of an evolutionary link has been proposed between B type Herbig Ae/Be stars and classical Be stars (Böhm & Balona 2000).

3. The Be star abundance as a function of the cluster age

There are only four galactic open clusters with a known distinctly high abundance of Be stars, namely more than 20% of Be stars among their observed OB stars. They are NGC 663, NGC 869, NGC 884 and NGC 3766. Assuming the ages determined in Sect. 2.1, the galactic clusters with the highest frequency of Be stars occupy the very narrow age interval from 13 to 24 Myr.

Grebel (1997) report on three more clusters in the Magellanic Clouds, with Be stars abundances comparable or even higher than the clusters referred to in the above paragraph. The ages of these clusters fall in the same range than those of the above galactic clusters. They are NGC 330 (19 Myr), NGC 2004 (20 Myr) and NGC 1818 (25 Myr). Notice that the age reported by Grebel for NGC 1818 is between 25 and 30 Myr, but looking at her Fig. 1 we find that the 25 Myr fits better the data. The same conclusion is reached by van Bever and Vanbeveren (1997).

Keller at al. (1999) also searched for Be stars in the clusters NGC 330 and NGC 346 in the SMC, and NGC 1818, NGC 1948, NGC 2004 and NGC 2100 in the LMC. They found a large amount of Be stars in all these clusters, with frequencies ranging from 13% to 34% of the clusters main sequence OB stars.

All the age determinations for the Magellanic Clouds clusters are derived from $BVRI$ photometry, and so we consider it less reliable than the ages obtained from *uvby* photometry, for the reasons explained in Sect. 2.1. Keller et al. (1999) consider these ages uncertain by factors of 2 to 3. Despite this fact, the coincidence between these ages and the age interval we determined from the *uvby* photometry of the galactic clusters is overwhelming. Only one Magellanic Clouds cluster falls very marginally outside of the age interval of 13-24 Myr, namely NGC 1818 (25 Myr).

In Table 2 we sum up the ages and Be star frequencies of all discussed "Be star rich" clusters. We consider within this category clusters with more than 20% of Be stars among their observed OB stars. Only the ages of the galactic clusters have been derived with the method proposed in Sect 2.1. For the Magellanic Clouds clusters there is not *uvby* photometry available. The quoted ages are from Grebel (1997) for NGC 330 and NGC 1818, and from Cassatella et al. (1996) for NGC 2100.

From the above, we conclude that the clusters with a high abundance of Be stars occupy a very narrow range of ages, namely between 13 and 25 Myr. For older clusters the percentage of Be stars decreases, as shown by Mermilliod (1982) and Grebel (1997). We have to study now the abundances in the younger clusters. There are not in the literature enough observational data to make a complete analysis, but we have been able to collect several pieces of evidence pointing towards the same conclusion: the very paucity of Be stars in clusters younger than 10 Myr. In the following paragraphs we will review some of them.

We have performed a first search in the WEBDA database of open cluster data (Mermilliod 1999). We found 64 clusters younger than 10 Myr. Among them, 7 clusters contain 3 or more Be stars. They include NGC 2244 (3 Be stars), NGC 6530 (18), NGC 6611 (20) and IC 2944 (8). All these clusters have been discussed in Sect. 2.3, where we show that their emission line objects are likely Herbig Be stars instead of classical Be stars. NGC 6823 (5) lies in a bright H II region with associated dark clouds (Stone 1988). NGC 7380 (3) is associated to the molecular cloud regions Sh2-142 and NGC 7380 E, and contains pre-main sequence stars among which several Herbig Ae/Be stars are identified (Chavarría-K. et al. 1994). IC 1590 (4) is embedded in the nebulosity of NGC 281, also identified as the bright H II emission region Sharpless 184 (Guetter & Turner 1997). One more cluster, IC 1805 (2) is located in an H II region, and associated to a large molecular cloud (Ninkov et al. 1995; Heyer et al. 1996). For the same arguments exposed in Sect. 2.3, we consider that the emission line objects in the last four clusters are likely to be pre-main sequence objects.

Table 2. The clusters with the highest Be star frequency in the Galaxy and Magellanic Clouds.

Cluster	Age	N_{Be}/N_{OB}	Ref.
Milky Way			
NGC 663	23	40%	Sanduleak (1990)
NGC 869	13	25–50%	Waelkens et al. (1990)
NGC 884	13	25–50%	Waelkens et al. (1990)
NGC 3766	24	36%	Shobbrook (1985, 1987)
SMC			
NGC 330	19	34%	Keller et al. (1999)
LMC			
NGC 1818	25	21%	Keller et al. (1999)
NGC 2100	15	28%	Keller et al. (1999)

Among the remaining 56 clusters younger than 10 Myr in the WEBDA database, one contains two Be stars (NGC 6871) and three one Be star (NGC 6383, NGC 7235 and Hogg 16). Even in these very few cases doubts still remain on the nature of the emission line objects. The emission line star in NGC 6383 has been studied by Thé et al. (1985), who cannot decide whether it is a classical Be star or a pre-main sequence object. 52 more clusters younger than 10 Myr in the WEBDA database have no Be stars detected so far.

In order to make a comparison with similar data, we have also searched the WEBDA database for clusters in the age interval 10-30 Myr, where we expect the maximum Be star abundance. We found 73 clusters, 28 among them containing Be stars. 13 clusters contain 3 or more Be stars, and 5 clusters 10 or more.

In Fig. 2 we present the frequency of clusters with different contents of Be stars as found in the WEBDA database, for three cluster samples: a./ Young clusters associated to nebulosities and undergoing high mass star formation; b./ clusters younger than 10 Myr without high mass star formation, and c./ clusters older than 10 Myr and younger than 30 Myr. It is easy to see that the Be star abundance in the last group is distinctly higher than in the group of young clusters without stellar formation, indicating

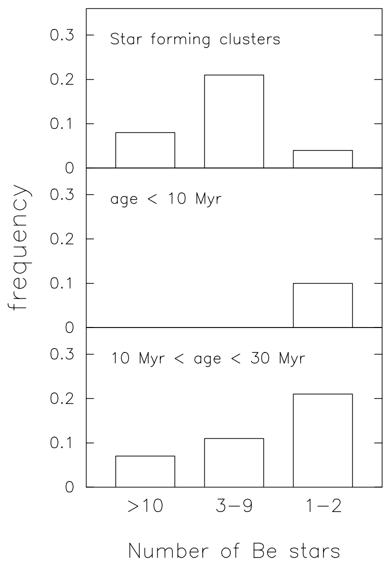

Fig. 2. Frequency of clusters with a given number of Be stars, for three different cluster samples. Top panel: clusters undergoing high mass stellar formation (24 clusters). Medium panel: Clusters younger than 10 Myr, without on-going stellar formation (40). Bottom panel: Clusters in the 10-30 Myr age interval (73). Data from the WEBDA database.

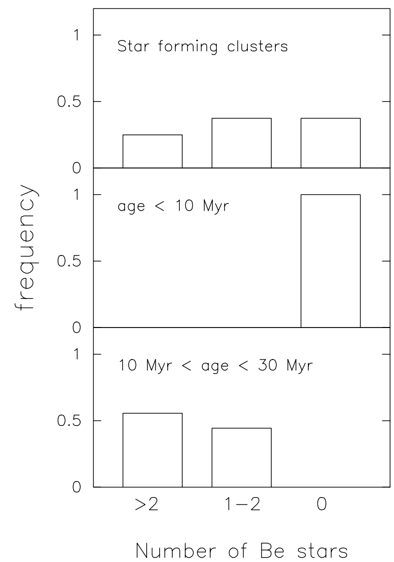

Fig. 3. Frequency of clusters with a given number of Be stars, found in the survey by Schild & Romanishin (1976), for the same samples that in Fig. 2.

that Be stars are much more frequent in the age interval 10-30 Myr than in the clusters younger than 10 Myr.

45 clusters in the WEBDA database in the 10-30 Myr interval have no Be stars detected so far. The existence of clusters without emission line objects in this age interval would raise important questions about the physical differences between clusters of the same age with and without Be stars. However, due to the sparseness and heterogeneity of the data we cannot prove that such clusters exist, and we consider more likely that the large number of clusters without detected Be stars came from the lack of appropriate surveys and the uncertainty in the age determinations. We base this opinion on the fact that, to our knowledge, every survey for Be stars in a cluster with a reliably determined age in the interval 10-30 Myr has produced positive results.

To illustrate this, we have analysed the results of the classic spectroscopic survey conducted by Schild & Romanishin (1976). They observed 9 clusters older than 10 Myr and younger than 30 Myr, and found Be stars in all of them. Conversely, they observed 8 clusters of 10 Myr or younger, without on-going stellar formation, and did not find any Be star among them. In Table 3 we present the results of the Schild & Romanishin survey, with an indication of the age of each cluster. Whenever possible, we have used ages determined from *uvby* photometry. For clusters lacking such determination, the age given in the WEBDA database is quoted. In Fig. 3 we present a histogram with the results of the Schild & Romanishin survey, for the same three groups considered in Fig. 2. It is apparent the difference in the frequency of Be stars for clusters younger and older than 10 Myr. It is noticeable that for some clusters in the age interval 10-30 Myr, namely NGC 457, NGC 581 and NGC 947, the frequency of Be stars found is similar that those for the known "Be rich" clusters NGC 663, NGC 869 and NGC 884. We consider it highly probable that the real abundances in all these clusters are similar, but the lack of systematic search in the former three has prevented the detection of their actual Be star content.

The survey of Schild & Romanishin (1976) is magnitude limited, and hence its completeness and limits in spectral type differ from cluster to cluster, depending upon their distance and reddening. In order to do a further check with samples for which we can assess the completeness, we have analysed CCD *uvby*β photometry for several open clusters obtained by Balona and coworkers (Balona 1994; Balona & Koen 1994; Balona & Laney 1995, 1996). They did not make any particular investigation of the Be star content of the clusters they observed, but we have searched their photometric lists for objects with emission in the Hβ line.

A β index equal to 2.55 corresponds to an equivalent width of the Hβ line equal to 0, i.e., a photospheric absorption line completely filled-in by emission (Fabregat & Torrejón 2000). Hence, $\beta < 2.55$ indicates that the Hβ line is in emission. We have searched the above referred to photometric lists for OB stars ($(b-y)_0 < 0.05$) with $\beta < 2.55$. This search will also detect, as well as classical Be stars, other kinds of early-type emission line objects, like Of and OBI stars. To exclude these stars we have introduced the additional restriction of $M_V > -4.5$. A proof of the reliability of this last restriction can be found in the following data: the two emission line stars in NGC 3293 brighter than -4.5 have spectral classification in the literature; they are star 3, with type B0.5Ib (Feast 1958), and star 4, type B0Ib (Morgan et al. 1955). In NGC 6231 there are 8 emission line stars brighter than -4.5, and 7 among them have spectral types given by Levato & Malaroda (1980). Two are OBI supergiants and three more Of. Even if the remaining three are Be stars – Oe in this case – this would not affect the main conclusions of

Table 3. Clusters searched for Be stars by Schild & Romanishin (1976). For each cluster we indicate the number of OB stars observed, number of Be stars found, age in Myr and the reference for the quoted age. Clusters referenced with 'SF' are clusters with on-going massive stellar formation.

Cluster	N_{obs}	N_{Be}	Age	Ref.
NGC 1893	18	1		SF
NGC 2244	21	0		SF
NGC 6530	22	3		SF
NGC 6611	29	4		SF
NGC 6823	17	0		SF
NGC 7380	18	1		SF
IC 1805	17	1		SF
IC 1848	10	0		SF
NGC 1502	24	0	7	Delgado et al. (1992)
IC 4996	21	0	8	Alfaro et al. (1985)
NGC 7235	11	0	9	WEBDA
NGC 6531	26	0	9	WEBDA
NGC 2129	11	0	10	WEBDA
NGC 6910	17	0	10	WEBDA
NGC 7510	7	0	10	WEBDA
NGC 6871	30	1	12	Reimann (1989)
NGC 581	18	3	13	WEBDA
NGC 869	31	1	13	This paper
NGC 884	21	5	13	This paper
NGC 457	21	3	14	WEBDA
NGC 957	14	4	15	WEBDA
NGC 6913	21	1	15	WEBDA
NGC 663	27	5	23	This paper
NGC 7160	24	1	23	WEBDA
NGC 2169	18	0	50	Peña & Peniche (1994)
NGC 7654	18	4	65	Danford & Thomas (1981)
NGC 6709	14	2	100	WEBDA
NGC 6475	14	0	130	WEBDA
Tr 2	26	1	130	WEBDA

this work, as we will comment on later. 60% of the Be stars in NGC 663, NGC 869 and NGC 884 observed by Fabregat et al. (1996) would have been detected by applying the above criteria. This percentage can be considered as the typical detection capability of a photometric survey, as discussed in Sect. 2.1.

After all these considerations, the final results of our survey in the photometric data published by Balona and co-workers are given in Table 4. Except in the case of NGC 2362, the ages reported have been derived from the pulsational properties of the β Cephei stars present in each cluster by Balona et al. (1997). As it can be seen the clusters in the age interval 4-10 Myr are almost lacking of Be stars. No Be stars have been found in the two younger clusters, with ages of 4-5 Myr. A few have been detected in the two older, with ages of 9-12 Myr.

4. Discussion

The general picture which emerges from the analysis in the previous section is the following: star forming clusters, associated to bright emission nebulae, are rich in emission line stars, but

Table 4. Clusters with CCD *uvby*β photometry obtained by Balona and co-workers. For each cluster we indicate the age, number of OB stars observed and number of Be stars.

Cluster	age	N_{OB}	N_{Be}
NGC 2362	5±2	33	0
NGC 3293	9.1±0.2	136	2
NGC 4775	11.7±1.5	121	3
NGC 6231	3.7±0.6	129	0

they are much likely pre-main sequence objects related to Herbig Ae/Be stars. When the nebula dissipates the process of star formation stops – at least with regard to the massive stars – and the clusters are devoid of early-type emission line objects. Classical Be stars start to appear in clusters with age of around 10 Myr, and reach their maximum abundance in the 13-25 Myr interval. For older clusters the Be star abundance decreases with age, as shown by Mermilliod (1982) and Grebel (1997).

The decreasing of the Be star abundance with the age after the 13-25 Myr peak is a reflect of the dependence of the Be star abundance with the spectral type. It is well known that the maximum abundance occurs for spectral type B1-B2 (Zorec & Briot 1997). Clusters older than 25 Myr have their turnoff at type B3 or later, and hence they are expected to contain lower abundances than clusters with B1-B2 main sequence stars. Clusters older than 100 Myr have their turnoff at B8 or later, and the lack of Be stars is an obvious reflect of the lack of any kind of B stars.

Conversely, the lack of Be stars in clusters younger than 10 Myr has evident implications on the evolutionary status discussion. These clusters have their turnoff at type B1 or earlier, and hence they have their B star sequence complete, including the spectral types for which the Be star abundance reaches its maximum. The lack of Be stars in these clusters implies that a Be star cannot be a very young object.

Be stars appear in clusters with turnoff at B1, and reach its maximum abundance in clusters with turnoff at B2. As most of the Be stars belong to these types, we have to conclude that Be stars are much closer to the end of the main sequence than to the ZAMS.

This result contradicts the finding of Mermilliod (1982) and Slettebak (1985), already mentioned in the introduction, who stated that Be stars occupy the whole main sequence band from the ZAMS to the TAMS. This affirmation is mainly based on photometric data, in the UBV system, of Be stars in open clusters. For a B star of a given subtype, the difference in $(B-V)$ between its position at the ZAMS and the end of the main sequence is lower than 0.1 mag. To firmly conclude that a Be star is in or near the ZAMS, a photometric accuracy of 0.02 mag. for the underlying star of the Be object would be required. If we consider all the problems which affect photometry of Be stars, this accuracy seems not to be within reach. Mermilliod (1982) uses the $(U-B)$ colour, for which the difference between ZAMS and TAMS is higher. But Be stars tend to move leftwards in the M_V - $(U-B)$ diagram due to the excess in the

U magnitude caused by the circumstellar emission in the Lyman continuum (Kaiser 1989). This effect can displace a strong emitter from TAMS to ZAMS and even leftwards. The excess in $(B-V)$ of circumstellar origin can amount up to 0.1 mag., while the variation in $(U-B)$ can reach 0.3 mag. The V mag. is also afected by variations up to 0.3-0.4 (Dachs et al. 1988; Pavlovski et al. 1997). Mermilliod already realized this effect when he states that the $(U-B)$ colours are affected by the Be phenomenon. Hence we consider our result based on the analysis of Be star abundances in open clusters more reliable that the results based on photometric data which are strongly affected by the circumstellar continuum emission. On the other hand, both authors are aware that most Be stars occur on the evolved part of the main sequence (Mermilliod 1982) and considerably off the ZAMS (Slettebak 1985).

There is additional evidence indicating that Be stars are somewhat evolved objects. In the younger clusters containing early-type Be stars, late type Be stars are scarce or completely lacking. This was first noted by Sanduleak (1979, 1990). He found 26 Be stars in NGC 663, and among them only 2 later than B5. His objetive prism survey was complete to mag. 14, which at the cluster reddening and distance reach the spectral type B6-B7V. He concludes that Be stars in NGC 663 are primarily confined to spectral types earlier than B5.

Capilla & Fabregat (2000) performed CCD Balmer-line photometry of NGC 663, NGC 869 and NGC 884. Their images are deep enough to cover all the B type range. They detected a total of 25 Be stars in the three clusters, and among them only two are later than B5.

Although, as mentioned above, the Be star distribution peaks at spectral type B1-B2 with an estimated abundance of 34%, the abundance in the range B5-B8 is around 20% (Zorec & Briot 1997). Hence, the lack of Be stars later than B5 in young clusters can be interpreted in the same evolutionary terms as before. In clusters with ages in the interval 13-24 Myr, stars earlier than B5 have spent more than a half of their life in the main sequence, while the late B stars are still in the first half of the main sequence phase. The Be phenomenon occurs among the former and not among the latter.

4.1. Be stars as post-mass-transfer binary systems

It has been suggested that Be stars could be the result of the evolution of close binary systems. The transfer of matter and angular momentum would produce the spin up of the mass gainer to very high rotation rates. It is well known that rapid rotation is a common characteristic of Be stars, and hence a key ingredient of the Be phenomenon. The products of close binary evolution are therefore good candidates to develop the Be phenomenon (Pols et al. 1991). Moreover, several Be stars are definitely post-mass-transfer systems. They are the Be/X-ray systems, in which a neutron star orbits an early-type Be star, accreting matter from the dense stellar wind and thereby generating X-rays. The properties of Be stars in Be/X-ray binaries are not different from those of the rest of Be stars. For a recent review of the properties of Be/X-ray binaries, see Negueruela (1998).

Our conclusions on the evolutionary status of Be stars are consistent with the hypothesis of the nature of Be stars as post-mass-transfer systems. The Be phenomenon would occur after the mass transfer phase in the evolution of a close binary. This would explain the scarcity of Be stars in very young clusters: the necessary time for the main sequence evolution of the primary star in the system has to be over before the mass transfer begins and the Be star is formed, and hence a Be star cannot be a very young object.

However, the interpretation of the Be phenomenon as the result of close binary evolution faces important problems, both theoretical and observational. The computations of Pols et al. (1991) only can account for about half the population of Be stars. The recent study of van Bever & Vanbeveren (1997) with updated models of close binary evolution reveal that only a minority of the Be stars (less than 20% and possibly as low as 5%) can be due to close binary evolution. On observational grounds, the models of close binary evolution predict a population of Be star plus white dwarf systems ten times more abundant than the Be/X-ray binaries. These systems should be observable as low luminosity X-ray sources. The search conducted by Meurs et al. (1992) failed in detecting the predicted population of Be+WD systems.

Hence we have to conclude that, despite the consistency with the results of our analysis, the model of the close binary evolution does not provide a satisfactory explanation to the Be star phenomenon. Moreover, it has to be considered that this model is ad hoc, because it only justifies the formation of a rapidly rotating B star, but does not explain how the Be phenomenon arises from it.

4.2. Evolution through the main sequence

The main conclusion of our study is that Be stars are evolved main sequence stars, closer to the TAMS than to the ZAMS. This would imply the existence of some evolutionary change able to produce the Be star phenomenon during the main sequence lifetime. This is not in agreement with the classical theory of stellar evolution, which predicts that the main sequence is a quiet evolutionary stage in which no major changes in the stellar structure occur.

However, in the modern literature there is a growing evidence of important changes which occur during the main sequence stage. Lyubimkov (1996, 1998) has shown that the abundance of helium and nitrogen in O and early B stars increases during the main sequence. This change is not monotonic. The initial helium abundance He/H = 0.08-0.09 is maintained during the first half of the main sequence lifetime. Subsequently, He/H abruptly increases approximately twofold in a short interval of relative ages $t/t_{\rm MS}$ (where $t_{\rm MS}$ is the main sequence lifetime) between 0.5 and 0.7, and this enhanced He/H remains constant until the main sequence stage is complete. Recent evolutionary models take into account this effect, and attribute the light element enhancement as due to early mixing produced by rotationally induced turbulent diffusion (Denissenkov 1994; Talon at al. 1997; Maeder 1997).

Our results are consistent with the Be phenomenon appearing at the same evolutive age $t/t_{\rm MS} \sim 0.5$. To show this we have to keep in mind that the highest percentage of Be stars corresponds to spectral types B1-B2 (Zorec & Briot 1997). The age of 10 Myr, where Be stars start to appear, corresponds to an evolutionary age of $t/t_{\rm MS}$ = 0.5 for a star of about 10 $M_\odot$ and solar metallicity (this and next paragraph discussion is based on data from Table 47 and Fig. 1 in Schaller et al. 1992). Such a star at this age has a spectral type of B1, where the abundance of Be stars reaches its maximum. In clusters younger than 8 Myr, stars are reaching the TAMS at 20 $M_\odot$ or higher, and at spectral types earlier than B1. The lower abundance of Be stars among these earlier types, and the low relative number of such massive stars explain the paucity of Be stars among these very young clusters. O8-9.5e stars can, however, start to appear at as early an age as 3 Myr, which can explain the few cases of clusters younger than 10 Myr with a few Be stars. NGC 6231, discussed in Sect. 3, could be one of these cases.

The maximum Be star abundance occurs between 13 and 25 Myr. 13 Myr corresponds with $t/t_{\rm MS}$ = 0.5 for a 9 $M_\odot$ star, at spectral type B1, i.e. at the begining of the maximum abundance of Be stars. 25 Myr is the end of the main sequence lifetime for a 9 $M_\odot$ star, at spectral type B3. Stars of lower mass reach the relative age of $t/t_{\rm MS}$ = 0.5 at spectral types of B3 or later, where the abundance of Be stars decreases. This explains the decreasing abundance of Be stars after an age of 25 Myr.

We propose the hypothesis that the Be phenomenon is an evolutionary effect, appearing half way of the main sequence lifetime, and is related to the light elements enhancement which occurs at the same evolutionary phase. There is a growing indirect evidence that magnetic fields near the stellar surface could be the cause of the enhanced mass loss which characterize the Be phenomenon (Peters 1998; Smith 2000, and references therein). The mechanisms proposed to explain the mixing at this stage, which imply movement of plasma near the stellar surface, coupled with the rotation of the star, could originate and maintain a magnetic field via a dynamo related effect. The characteristic high rotational velocity of Be stars would play a major role in: i./ inducing the movement of matter via turbulent diffusion; and, ii./ enhancing the magnetic field strength via the dynamo effect. Hence our hypothesis provides a natural explanation of the influence of high rotational velocity in the Be phenomenon.

A direct proof of this hypothesis could be obtained by studying whether Be stars have an enhanced helium abundance. Unfortunately, the contamination of the photospheric spectrum by the circumstellar emission lines makes the abundance analysis of Be stars an almost impossible task. Such analysis can be performed in Be stars observed in a disk-loss phase, i.e., in a phase in which the circumstellar disk has dissipated and the photospheric spectrum is directly observable. This has been done by Lyubimkov et al. (1997) for the Be star X Persei, and they obtained an enhanced helium abundance of He/H = 0.19. However, this case is not conclusive, because X Persei is a Be/X-ray binary which in the past underwent mass transfer, and hence it is not possible to know whether the helium overabundance is due to internal processes in the current primary star or whether it is caused by external accretion from the original primary. Helium abundance studies of isolated Be stars observed during disk-loss phases are required to proof our sugestions.

5. Conclusions

We have presented a study of the abundance of Be stars in open clusters as a function of the cluster age, using whenever possible ages determined through Strömgren $uvby$ photometry. For the first time in studies of this kind we have considered separately classical and Herbig Be stars.

The main results obtained can be summarized as follows:

- Clusters associated to emitting nebulosities and undergoing stellar formation are rich in emission line objects, which most likely are all pre-main sequence objects. No bona fide classical Be star has yet been identified among them.
- Clusters younger than 10 Myr and without associated nebulosity are almost completely lacking Be stars, although they have a complete unevolved B main sequence.
- Classical Be stars appear at an age of 10 Myr, and reach the maximum abundance in the age interval 13-25 Myr.

We have interpreted our results in the sense that the Be phenomenon is an evolutionary effect which appears in the second half of the main sequence lifetime of a B star. This conclusion is supported by other facts, like the lack of late-type Be stars in young clusters rich in early-type Be stars.

We propose the hypothesis that the Be phenomenon could be related to main structural changes happening at an evolutionary age of $t/t_{\rm MS}$ = 0.5, which also lead to the recently discovered non-monotonic helium abundance enhancement. The semiconvection or turbulent diffusion responsible of the helium and nitrogen enrichment, coupled with the high rotational velocity, can originate magnetic fields via the dynamo effect. There is evidence that many observed phenomena are due to Be star photospheric activity related to the presence of magnetic fields. Our hypothesis provides a natural explanation of the relationship between the Be phenomenon and the high rotational velocity characteristic of Be stars.

It should be noted, however, that our results on the Be star frequencies in open clusters came from scarce and inhomogeneous sets of data, and this leads to a somewhat speculative component in our conclusions. To check our results and proposed explanations the following observational data would be of critical importance:

- A systematic study of the Be star frequencies in a significant number of clusters of different ages, both in the Galaxy and in the Magellanic Clouds. It would be of exceptional interest to know the abundances in Magellanic Clouds clusters younger than 10 Myr and with high-mass stellar formation finished yet.
- The determination of cluster ages in an homogeneous system. We propose for this purpose the use of the Strömgren $uvby$ system.

- The determination of the helium and light elements abundance of Be stars undergoing phases of disk-loss.
- In a more general context, the determination of the helium abundance in B stars with evolutionary ages $t/t_{\rm MS} > 0.5$. Early type B stars in clusters with turn-off at B1-B2 would be specially well suited for this purpose.

We are currently undertaking observational programs to address the above questions.

To conclude, we would like to comment that in the recent years, many relations and cross-links between classical Be stars and several other types of peculiar hot stars have been put forward, clearly showing that the Be phenomenon is not just an isolated problem of the stellar astrophysics. On the other hand, the results mentioned above on light element enhancements in the atmospheres of hot stars during their main sequence lifetime are not compatible with the classical stellar evolutionary models, and demonstrate that there are important lackings in our knowledge of massive star evolution. In this paper we propose that both phenomena are related, and hence, the understanding of the Be phenomenon could be the clue for the advance in our understanding of major issues in massive star formation and evolution.

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